**US Army Corps
of Engineers**®
Engineer Research and
Development Center

Sensor Technology for Weather and Terrain

Andrew W. Harrell

September 2000

20001107 006

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

Sensor Technology for Weather and Terrain

by Andrew W. Harrell

Geotechnical Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

DTIC QUALITY INSPECTED 4

Contents

Preface

Members of the staff of the Geotechnical Laboratory (GL), U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS, conducted this study during July 1998 through November 1999. Funding for the study was provided under Project Lines of Communication Assessment and Repair of Roadways PE 62784/AT40.

The study was conducted under the general supervision of Dr. William Willoughby, Acting Chief, Mobility Systems Division (MSD), GL. Dr. George Mason, MSD, supplied the Time Domain Reflectometer (TDR), soil moisture readings in Table 3, Appendix A. Dr. Donald Hoock, Weather Exploitation Branch, Battlefield Environment Directorate, U.S. Army Research Laboratory, White Sands Missile Range, New Mexico, assisted by supplying much of the information in the report about current U.S. Army satellite sensing of soil moisture content. Mr. Gene Barnes, Air Force Combat Weather Center, Hurlburt Field, Florida, provided demonstrations of current weather software techniques and their intended use.

This report was written by Dr. Andrew Harrell, MSD, GL. Drs. Pat Sullivan, George Mason, William Willoughby, and David Horner, GL, provided valuable comments that were incorporated into the final report on the exposition of the study results. Mr. Jody Priddy, MSD, GL, helped with the proof of the Conversion Formulae in Appendix B.

At the time of publication of this report, Director of ERDC was Dr. James R. Houston, and Commander was COL James S. Weller, EN.

Conversion Factors,
Non-SI to SI (Metric)
Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
inches	2.54	centimeters
pounds (force)	4.44822	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
square inches	6.4516	square centimeters

1 Introduction

Background

One of the primary effects that weather has on combat engineering is related to the combat force's mobility (vehicle trafficability). In this regard, weather information, such as precipitation history, surface observations, and forecasts, has not normally been readily available to the unit. The individual vehicle speed predictions and movement schemes that determine the unit's mobility are greatly affected by the soil type and moisture content. GO and NO-GO mapsheet regions based on the individual vehicle speed predictions given by the NATO Reference Mobility Model (NRMM) can vary greatly depending on the history of rainfall amounts over a particular terrain. Rainfall amounts at specific terrain locations determine the soil strength for various soil layers (0-6 in., 6-12 in., 12-18 in., 18-24 in., 24-30 in., 30-36 in.)[1] in the U.S. Army Engineer Research and Development Center's (ERDC) Soil Moisture Strength Prediction Model (SMSP) (Sullivan and Bullock 1997). Current accuracy requirement is for ±5 percent (weight of water to weight of dry soil). Predictions are based on daily data.[2] An archival history for the past season may be necessary to initialize the model for frost depth determination. Precipitation rate is currently not required.[3] Given this information, the soil strength values are matched against the requirements for traction and the vehicle cone index (VCI)[4] in the NRMM to determine the vehicle's speed and trafficability.[5] Other terrain factors, such as surface roughness,[6] vegetation stem diameter and spacing, obstacle type and spacing, visibility, and slope are also considered.

---

[1] To convert inches to centimeters, multiply by 2.54.

[2] At a minimum, three basic climatic input parameters are required by SMSP (Sullivan and Bullock 1997) to determine soil moisture and, ultimately, soil strength: location, daily precipitation, and evaporation.

[3] Except as outlined elsewhere (Harrell 1998) for flood control hydrologic studies.

[4] The VCI can be predicted from empirically derived formulas relating vehicle characteristics (gross weight, spatial weight distribution, tire characteristics, etc.). These predictions are usually supplemented by actual vehicle test experiments. Tests are conducted under various soil conditions and numbers of vehicle passes.

[5] The term trafficability, when it is used in mobility programs, usually includes the effect of multiple vehicle passes on the load bearing capacity of the soil.

[6] Surface roughness for vehicle speed predictions is measured in root-mean squared inches. It is computed by making a series of elevation readings at 1-ft increments along a terrain profile for 152 m (500 ft) or more. This series is then detrended, smoothed by exponential weighting, and the root mean square computed.

Weather factors also have a large influence on the movement capability of the unit of combat units in exercises, wargames, and actual tactical operations. The unit movement speeds affect the times of exposure of the attacker to the defender's weapons and his ability to relocate to concentrate or disperse his combat power. Obstacle effectiveness in terms of attrition of forces is largely driven by exposure time. At present, for tactical operations, programs such as the Army's Maneuver Control System (MCS) and the ERDC Obstacle Planning System (OPS) are linked to the Terrain Evaluation Model (TEM) as a specific software medium in which these effects can be represented.[1] For combat simulations, such as JANUS, VIC, CASTFOREM, JWARS (JWARS is currently in development), and ModSaF/OneSaF,[2] the degree that weather can influence or change the combat engineering function depends on the details of how these functions (along with the weather function) are actually implemented into the simulation.[3]

Purpose

The purpose of this report is to review weather effects on soil moisture and combat engineering. It will consider the current means of obtaining soil moisture information from weather models, surface observation reports, and remote sensing sources. It will explain how this information is used to predict the effects on vehicle performance. And it will concentrate on explaining the methodology used by different types of ground moisture probes, and in particular, the time domain reflectometers (TDR). Specifically, it will consider how the measurements that the TDR probes give can be validated and calibrated for different soil types. Soil moisture information affects operational considerations for combat engineering and ground mobility considerations in particular. And, it has significant applicability to simulations and wargames.

Scope

The scope of this study was limited in several respects. It did not consider the details of operating the soil moisture probes or of implementing soil moisture measurements into simulations or wargames. Different ways of modeling precipitation or the areal flow of groundwater are not discussed. Tables of soil moisture values are currently provided for only one soil type and type of moisture probe. Thus, conclusions about the usefulness of different types of probes for various soil types are limited in this respect.

---

[1] Speed predictions for these tactical decision aids are computed using the NRMM. According to current plans, the TEM is scheduled to be replaced by Joint Mapping Toolkit software (which will also use NRMM computed speeds for trafficability predictions).

[2] High resolution distributed simulations for Ground Forces that model individual vehicular movement.

[3] The previous simulations may or may not have predefined routes whose traverse times are normally determined from NRMM speed predictions. For VIC and JWARS, at present, weather is not explicitly represented in terms of unit movement unless it is factored into the speed prediction program. For the other models, higher resolution entity level movement is considered.

2 Obtaining Soil Moisture Information

Weather Model

The Integrated Meteorological System (IMETS) (Department of Defense (DOD), Air Force Weather Agency 1999) is the Army meteorological component of the Intelligence and Electronic Warfare (IEW) subelement of the Army Battle Command System (ABCS). It was developed to supplement and assist the Air Force Staff Weather Officer assigned to work in the ABCS environment. IMETS obtains actual historical and current rainfall amounts from observation profiles, surface observation reports, and from the Army's Battlefield Forecast Model (BFM).[1] However, at present BFM does not use the surface observation rainfall reports as input to its numerical predictions. Another means of obtaining soil moisture content information is from satellite remote sensing observations (assuming cloud cover does not affect the satellite sensor's measurements).

Thus, to provide rainfall data for the SMSP, there are three options:

a. Rely on surface weather observation reports.

b. Improve the BFM model to more accurately forecast thunderstorm rainfall amounts.

c. Use a set of inference algorithms along with satellite information to estimate the soil moisture content (real-time).

---

[1] The BFM supplements the Navy's Operational Global Atmospheric Prediction System (NOGAPS) forecasts and the Air Force Meteorological Model Version 5 (MM5) by taking into account surface features in the land terrain using terrain surface/atmosphere interaction equations. However, it does not model the areal coverage of thunderstorm rainfall down to the 100-m × 100-m resolution required by the SMSP. It takes about 2 hr to run to predict the values of up to 60 variables related to the weather. If the Digital Terrain Elevation Data (DTED) hasn't already been loaded for the area of operations, it takes another 4 hr to initialize.

Surface Observation Reports

Surface weather observation reports outside the United States require a stand-alone reporting system, which is not currently part of the IMETS system. Several years ago, a World Meteorological Reporting System was considered (but not funded) by the U.S. Army which would use automated rainfall sensors to collect hourly data. In the Joint Army/Air Force Training Manual FM 34-81-1/ AFM 105-4 (U.S. Army Training and Doctrine Command 1989a,b), a procedure has been delegated for tactical units to report weather observations. Military intelligence battalions supply trained observers, which submit forward area limited observing program (FALOP) reports to the G2 or S2. The staff weather officer (SWO) at the Corps/Division Aviation Brigade collects these reports. The G2 specifies the collected data in the FALOP, which can include type of precipitation and intensity along with road, ground, and water conditions. Another source of information is to authorize Synthetic Aperture Radar (SAR) aircraft data collections. In this case, the soil moisture determination depends on its sensitivity via the soil dielectric constant. Their data are high resolution (30 m to 100 m) and can determine the soil moisture in the top 5 cm to 10 cm of the soil profile. However, normally, these data are only collected infrequently and are affected for calibration purposes by surface roughness, snow, and vegetation cover.

Obtaining Information from Remote Sensing Sources

The BFM model presently does not discriminate rainfall regions to the degree needed to predict mobility corridors. However, the theoretical model could be improved by adding higher-order terms in the numerical approximations the model uses.

To integrate satellite imagery into the IMETS displays, Hughes small tactical terminals would be required. Such a system is presently being considered for procurement by the U.S. Air Force. If selected, the following systems would provide supplemental data:

a. The Navy Orbview2 Sea-WIFS data consisting of eight visible to near-infrared spectral bands at 1-km × 1-km resolution.

b. The National Oceanographic and Atmospheric Administration's (NOAA) 6- and 12-hr data (Advanced Very High Resolution Radiometer (AVHRR) consisting of middle-to-far infrared data for five spectral bands at 1-km × 1-km resolution).

c. The Defense Meteorological Satellite Program (DMSP) special sensor (microwave T1, T2 sounding and imaging) satellite data at 20- to 50-km × 20- to 50-km resolution.

These spectral bands are appropriate for use in soil moisture profile estimation. One estimation algorithm uses the 1-km × 1-km NOAA AVHRR data and

considers a normalized difference of vegetation index (NDVI) to indirectly esti-
mate soil moisture (Wetzel and Woodward 1987).[1] This approach has good
spatial resolution but is an averaged procedure over time. Another procedure
uses the DMSP special microwave sensor data to directly estimate the current
time soil moisture content. A microwave polarized difference index (MPDI)[2]
(Teng 1993) algorithm or a weighted average, Antecedent Precipitation Index
(API),[3] may also be used. Linear regression parameters are then computed
between the special sensor microwave imaging (SSM/I) brightness temperature
(TB) and the API. This relationship allows API to be estimated from TB.

The advantage to estimating the soil moisture by starting from the passive
infrared thermal brightness is that the regression relationship that determines TB
is largely independent of soil type. This makes measurements at lower grid
resolutions more valid.

Another approach, which has been implemented by the NOAA, uses the
difference between the 85-GHZ and 19-GHZ horizontally polarized radiation
from the DMSP special sensor microwave.[4]

However, because of the spatial resolution used, the MPDI, the API, and the
NOAA approaches (20 to 50 km × 20 to 50 km) do not provide enough informa-
tion, by themselves, for mobility speed predictions.

Some possible ways to increase the remote sensing resolution would be to use
different combinations of multiple sensors in a single satellite, along with a
maximum a posteriori statistical test or multiple satellites, which are spatially
separated in an interferometer arrangement.

---

[1] The measure of effectiveness: -1< (channel 2 − channel 1)/(channel 2 + channel 1) < 1 can be
used as a measure of a longer-term effect of rainfall as a result of greening.

[2] MPDI = Vertical Polarization - Horizontal Polarization.

[3] $API_{j+1} = K_j (API_j + P_j)$. P_j is the amount of precipitation during day j. $K_j = \exp(-E_j/W)$ is a reces-
sion weighting coefficient for day j. E_j measures the evaporation during day j. W is the maximum
depth of soil water available for evaporation.

[4] A 5-day moving average (SWI) is computed for each grid. These data are then averaged spatially
according to the formula: $SWIZ_i = (SWI_i\text{-}\underline{SWI})/sigma*SWI_i$. (sigma = standard deviation of the
spatial part of the observations). The SWIZ variable is then scaled into three categories: (a) 1 to 2,
wet; (b) 2 to 3, extremely wet; and (c) ≥3, potential for flooding, posted to the website as a visual
display and archived.

3 Types of Soil Moisture Probes

There are four families or types of moisture probes:

a. *Time Domain Reflectometers (TDR).* These instruments send out a series of pulses; the times of travel of the pulses are measured and the dielectric constant of the medium is computed from the relationship[1] $E_b (c/v)^2$, where c is the velocity of light, v is the velocity of the wave, and E_b is the bulk soil dielectric constant. The presence of water in the medium affects the speed of transmission of the electromagnetic waves.

b. *Correlation.* These instruments work by using an assumed relation or correlation between the soil moisture and soil temperature (which is determined separately). The temperature is measured and the moisture is then computed from the assumed relationship.

c. *Conductivity/Resistivity.* These types of instruments consist of a long metal rod with a dial that emits an electric pulse and measures change in voltage. The reading provides an indication of the soil moisture content. ERDC developed a diacon soil moisture reflectivity instrument in 1962. The U.S. Army Corps of Engineers Cold Regions Research and Environmental Laboratory (CRREL) presently uses this type of instrument to measure soil moisture in cold regions.

d. *Capacitance Sensors and Frequency Domain Sensors.* Capacitance sensors are made up of a pair of electrodes and use an oscillator to generate an A/C field, which is applied to the soil to detect changes in soil dielectric properties linked to variations in soil-water content. Frequency domain sensors are similar but use a swept frequency. These sensors operate at lower frequencies (100 MHZ or less) than TDR systems and are therefore better at detecting bound water in fine particle soils, but such systems operating at lower frequencies are more susceptible to salinity errors.

---

[1] This is a simplified formula that follows from the relationship:

$v = c /((\varepsilon '[1+(1+\tan^2 \delta +1)^{1/2}])/2)^{1/2}$ when the electrical loss δ is low. Where, v is propagation velocity of a TDR electromagnetic signal; ε' is the real part of the relative dielectric permittivity, and c is the speed of light. The reference papers of Topp, Davis, and Annan (1980) and Lundien (1966a,b) have justified this simplifying assumption in the case where the surrounding medium is soil.

e. *Soil Moisture Probe Instruments.* In the Internet site
       http://www.sowacs.com, Alan Robock provides information about the
       many other types of soil moisture instruments. Other types use reverse
       osmosis (granular matrix sensors) gypsum blocks to measure electrical
       resistance.

The readings for all of the aforementioned types of instruments are affected by
temperature. The TDR and Resistivity types require a power source to operate.
Within 30 min they provide a stable reading. But, most moisture probes require a
week or two of time to settle to give the most accurate measurements.

A Short History of the TDR Methodology

In 1966, the U.S. Army Waterways Experiment Station (WES), now the
U.S. Army Engineering Research and Development Center (ERDC), Vicksburg,
MS, published the results of their experimental investigations of the potential for
the use of various parts of the electromagnetic spectrum[1] to obtain soil measure
estimates. In the report (Lundien 1966a,b) methods were determined to discrim-
inate soil-type and soil-water contents using the Ka, X, C, and P radar bands.
Soil samples of Sharkey clay, Richfield silt loam, Putnam clay, Putnam silt loam,
and Perlite were placed between metal plates in a wooden-arched radar test facil-
ity, and the proportion of transmitted radar energy that was reflected from the
samples was measured. Radar reflectances were measured and the radar signa-
tures computed for water in prepared soil samples with the water placed at
various depths. These signatures consisted of the dielectric constants and con-
ductivity of the soil and the phase factors necessary to calibrate the measure-
ments. A wavelength method based on the measurement of the dielectric
constant (similar to the approach later developed for the TDR probe) and surface
reflection method were used to discriminate the soil types and water contents. In
1980 Topp, Davis, and Annan studied the determination of soil-water contents
from measurements in coaxial transmission lines. They found that for the fre-
quency range of 20 MHz to 1 GHZ there existed a relationship between the
dielectric constant and the water content that was fairly independent of soil type.
An empirical formula (for multiple soil types) in the form of a third-order poly-
nomial was proposed by Topp, Davis, and Annan (1980) to represent this rela-
tionship between the bulk dielectric constant and θ_w (the volumetric water
content). Given a soil sample in the field, the intensities of the reflected pulses
could then be measured and local maxima and minima in the graph of the reflec-
tances versus frequencies determined. An appropriate mathematical search
algorithm was needed to compute the points necessary to characterize the wave
travel time. In another paper (Dalton et al. 1984), TDR signal attenuation was
related to the bulk soil electrical conductivity. This relationship and the afore-
mentioned empirically determined formula allow the voltage traces to be con-
verted into percent volumetric water contents. In the paper by Roth et al. (1990),

---

[1] 0.76- to 5.00-micron; 297 megacycles (P radar band); 5,870 megacycles (C-radar band);
9,375 megacycles (X radar band); 34,543 megacycles (Ka radar band); 0 to 2.82 million electron
volts (MEV) gamma ray.

the soil material is considered to be a three-phased (soil, water, air) system and the composite dielectric number is determined by parameters representing the percentages of the different phases that are present. The values of the phase parameters for a given in situ soil sample are determined a posteriori by minimizing[1] the squares of the residual errors of radar-determined volumetric measurements from the matching gravimetric water content soil samples. In this paper the researchers found that, for several soil types and radar frequencies, the temperature significantly affected the accuracy of the empirical formula used to estimate the value of the dielectric constant based on the travel time of the TDR waves.

Further Information about TDR Probes

Electronic Design Systems, Inc., in Canada makes the TDR instrument that Vaisala Corp. and Raytheon Corp. are using for a Hurlburt Field, Florida, Operational Test and Evaluation (OTE) field study. Also, the U.S. Forest Service currently uses this type of instrument in its field studies.

There is one possible theoretical limitation to using this approach to determine water content. Recent theoretical investigations have determined that though the dielectric constant-water content relationship is fairly independent of soil type, it does, however, depend on soil temperature (Roth et al. 1990, Wraith and Or 1999a,b). This follows theoretically when one realizes that the dielectric frequencies are partly determined by rotationally vibrating molecules creating viscous forces in the unbound water around the soil. The amount of this effect will, of course, be dependent on the soil temperature. The reference by Roth et al. 1990 gives a mathematical procedure to take account of this by considering the soil as composed of three separate material phases: water, air, and soil.

The Vaisala/EDSI instrument has four sections, which give readings. These sections measure the soil moisture at 10 cm, 20 cm, 30 cm, 40 cm depth below the surface.

---

[1] The mathematical procedure for doing this is called the Levenberg-Marquardt algorithm. Sample code for implementing the algorithm is contained in the reference (Press et al. 1986). Details of how this algorithm can be implemented and compared to other mathematical optimization approaches are contained in the reference (Harrell 1995).

4 Accuracy of Probe Measurements – Comparing Gravimetric and Volumetric Measurements

ERDC obtained several of the Engineering Design System Integration (EDSI) probes and this year conducted a field program to make a series of TDR volumetric soil moisture readings with it in clayey soils near Mud Lake, Louisiana. Measurements were made in May 1999 and are shown in Appendix A, Table A1. The TDR values shown are averages from probes placed at five stations. These TDR volumetric measurements were supplemented with standard dry density by weight gravimetric soil moisture measurements[1]. This allows the accuracy of soil moisture instrument's measurements to be compared with the current standard method of known accuracy. Cone index penetrometer readings were also taken.

The reference by Fredland and Rahardjo 1993 provides a formula for comparing volumetric moisture content and standard, by weight, dry density moisture contents:

$$\theta_w = (S * w * G_s)/(S + w * G_s)$$

In this formula, S is the degree of saturation:

where

S = $(V_w)/(V_v)$ is the volume of water in soil type/volume of voids in soil type

---

[1] Because of the soil hydraulic suction, volumetric water content percentages are not the same as gravimetric water content percentages. The amount of volume that the soil particles take up in a given soil space depends not only on the particle characteristics and sizes, but also the hydraulic suction and pressure bearing on the soil. The paper by Assouline and Bruand (1998) discusses some of the various ways to model the relationship between the capillary head and the volumetric water content for various soil types.

$\theta_w =$ $(V_w)/(V)$ is volume of the water in the sample/volume of the sample, i.e., the volumetric water content

$w =$ $(W_w)/(W_s)$ is the weight of the water in the sample/weight of the soil in the sample, i.e., the gravimetric (standard dry density) water content

$G_s =$ ρ_s/ρ_w is the density of solids in the soil sample/density of water in the soil sample. Or, the unit weight of the soil sample/unit weight of water, i.e., the specific gravity of the soil type

The validity of the aforementioned formula for θ_w follows from these definitions. The complete derivation of the formula is given in Appendix B.

If soil porosity is assumed constant, from the above it follows that $w = \theta_w / G_s$. Since w should be expected to vary according to the situation in situ, w can be determined for each different set of data.

However, because the porosity of soil types varies so much, it is necessary to consider this effect as a separate variable in the relationship. Suction pressure can also affect the measured values in the soil moisture equations. In general, differences in amounts of water at various depths in the soil create a suction head pressure. This pressure can be directed upward or downward, depending on the pressure differential caused by surface precipitation or existing groundwater in the water table of the soil. When using the TDR measurement methodology, volumetric water contents are computed from the radar travel time measurements. However, to compare the TDR measurements to actual values, gravimetric soil sample calculations are used. Thus, these two different definitions of water content must be reconciled. But, as mentioned above, the conversion factors are not constant for a given soil type but depend on the amount of suction head pressure in the soil at a given time.

For a fat, clayey soil type, the reference from Terzaghi and Peck 1948, page 31 gives a value for G_s which is approximately 2.70. As explained in the reference from Tuma and Abdel-Hady (1973), page 33, according to the Unified Soil Classification System (USCS) fat clayey (CH) soils are fine-grained of high plasticity (liquid limit > 50). Terzaghi and Peck (1948) also list, on the same page cited above, a range of values of approximately 37 to 92 (percent) for n, the porosity, of a fat, or colloidal, clayey soil. Thus, from the relationships:

$S =$ θ_w/n, the degree of saturation of this soil type, can be determined (where n is the soil porosity), and

$n =$ V_v/V, the volume of the voids over the volume of the soil sample.

Substituting these expressions into the first formula listed in this section one can express θ_w as a function of S, w, and G_s: and,

$$\theta_w = w * G_s * (1-n)$$

Without any other information, it is of interest to find a value for the porosity based entirely on a categorical classification of the soil type. Perloff and Baron (1976) and Terzaghi and Peck (1948) list the porosity of soft clay with low organic content as 66 percent.

From examination of the previous formulae, it can be seen that the observed gravimetric water contents should differ by a scalar factor from the observed volumetric water contents. Thus, the porosity can also be computed a posteriori from the observations. Taking the averages at different depths of the gravimetric and volumetric observations during May gives a factor of 1.38, and

$\theta_w = 1.38*w$ which implies a porosity (n) of 48, which is within the predicted limits for this type of soil.

Adjusting the columns of the observations using this factor gives the values shown in Appendix A, Table A2. The same procedure was followed for the observations in the month of June, with the results of porosity for the soil of 48 and percent errors between the gravimetric and volumetric soils which are shown in Appendix A, Table A3.

5 Issues, Conclusions, Recommendations

Issues

ERDC, Vicksburg, is concerned that the soil moisture percentage for which the TDR is designed and tested (sandy soils and soil moistures less than 10 percent (Jamilkowski 1998) and (DOD Air Force Combat Weather Center (AFCWC) 1999) may not be high enough for those needed to permit vehicular trafficability calculations (measurements of all types of soil including sandy, clay, and muskeg[1] soils with soil moistures of from 0 to 50 percent are normally required).

Recently NOAA has funded Dr. Alan Robock at Rutgers University (http://climate.envsci.rutgers.edu/soil moisture) to develop and validate a set of global soil moisture measurements. He has been working with Dr. Konstantin Vinnikov at the University of Maryland and Dr. Nina Speranskaya at the St. Petersburg Meteorological Institute in Russia (Robock et al. 1998; Entin et al. 1977; Vinnikov et al. 1999). In these papers, they measure average soil moisture in terms of centimeters of wetness in the first 1 m of soil depth. They also use statistics to demonstrate that the horizontal spacing of the soil moisture probes required for purposes of predicting agricultural drought is approximately 100 km. Mathematical spatial interpolation algorithms can then be used to contour the information. Since vehicle trafficability information is usually displayed in 100-m × 100-m or 15-m × 15-m grids, spacing of the probes for these purposes must be much closer than 100 km. However, statistical tables of climatic rainfall data can be used to supplement the ground truth information.

Conclusions from Test Data

Since the averages of the observations for May and June were computed separately, having the porosity factor the same in both cases supports the validity of this method of calculation. Since the gravimetric and volumetric measurements are related by a constant factor, it appears more useful to calculate the

---

[1] A soil type which is a mix of peat and other highly organic compounds found in previously glacial areas such as Canada and the North German Plain.

porosity of the soil (n) from the observations than to use a value obtained from an apriori USCS classification procedure. It may be necessary to recalibrate the probes when they are used in different soil types. Thus, extensive testing and measuring in all soil types should be done before the measurements are used for operational intelligence. If the TDR approach does not work in all soil types, then several different types of probes must be developed for specific uses.

Recommendations

The references from Jamilkowski (1998) and DOD AFCWC (1999) contain the operational requirements for the modifications to the TACMET system, which include soil moisture, probe information. It states that the soil moisture must be measurable between −5 deg C and +50 deg C, with an accuracy of ±5 percent in a range of 30 to 100 percent relative to saturation. The best way to test this accuracy is to compare the probe readings with standard by weight-soil-moisture measurements. As it is currently configured, the readings from the Vaisala/Raytheon probe must be converted from volumetric to gravimetric readings. The procedures discussed in this report are an example of one way to do this conversion for clay type soils. Because the accuracy and the baseline calibration of the instrument should be expected to vary over different soil types, tests should be conducted over a range of soil types. The soil types tested should include those expected to be encountered in vehicle trafficability studies.

Tests at the ERDC, Vicksburg, have determined that a period of 3 to 4 weeks is required for the readings of the instrument to stabilize. This limits its use for reconnaissance missions. The TACMETS (DOD AFCWC 1999) has a capability to transmit recorded data over a radio frequency transmitter if a threat communications security officer approves such transmission. It should be possible to use personnel to emplace two or three of the probes and then have the data stored and transmitted to overflying aircraft or satellites. For this specific application, it may be desirable to produce a stand-alone version of the probe in which the data recording capability is independent of the other meteorological sensors on the TACMET. This would simplify its use in forward areas that aren't necessarily near airfields.

There now exist several worldwide geographical databases of soil type information. NIMA funded Texas A&M to develop the databases some years ago. In conducting its OT&E test plan for the soil moisture probes, the Army should select one of these databases and ensure it's accuracy is verified for the soil types which are likely to be encountered in current operational plans.

References

Assouline, S., and Bruand, A. (1998). "A conceptual model of the soil water retention curve," *Water Resources Research* 34, 223-231.

Campbell, G. S. (1974). "A simple method for determining unsaturated conductivity from moisture retention data," *Soil Science* 117, 311-17.

Dalton, F. N., Herkelrath, W. N., Rawlins, D. S., and Rhoades, J. D. (1984). "Time-domain reflectometry: Simultaneous measurement of soil water content and electrical conductivity with a single probe, for measuring soil water content and bulk soil electrical conductivity," *Science* 224, 989-990.

Das, Braja M. (1990). *Principles of geotechnical engineering.* PWS-Kent, Boston MA.

Davis, B. R, Lipscomb, E. B., and Knight, S. J. (1995). "Terrain Analysis by Electromagnetic Means, Report 1," Technical Report 3-693, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Department of Defense, Air Force Combat Weather Center. (1999). TACMET Mod OT&E, Hurlburt Field, Florida.

Department of Defense, Air Force Weather Agency. (1999). "Operational Requirements Document (ORD) for Integrated Meteorological System (IMETS)," Washington, DC.

Entin, J. T., Robock, Alan, Vinnikov, K. Y., Qiu, Shuang, Zabelin, V., Jiu, S., Namakhai, A., and Adjasumen, T. (1999). "Evaluation of global soil wetness project soil moisture simulations," *Journal of the Meteorological Society of Japan* 77,183-198.

Frelund, D. G., and Rahardjo, H. (1993). "Soil mechanics for unsaturated soils." Wiley, New York, N.Y.

Harrell, Andrew W. (1996). "Methodology for the curve fitting of nonlinear ride curves." *Transactions of the Mathematics, Computer Science, Statistics Div.* MS Academy of Sciences, MAS Report 96-1 Sixteenth Annual Mtg. Feb. 1996, West Point, NY.

Harrell, Andrew. (1998). "Weather impacts on combat engineering," U.S. Army Research Laboratory, Information Science and Technology Directorate, Battlefield Environments Division, White Sands Missile Range, New Mexico.

Jamilkowski, Michael. (1998). "Technical requirements document (TRD) for the tactical meteorological (TACMET) observing system modification," U.S. Air Force Weather Agency, Washington, DC.

Lundien, J. R. (1966a). "Terrain analysis by electromagnetic means, report 2," Technical Report 3-693, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

_____. (1966b). "Terrain analysis by electromagnetic means, report 3," Technical Report 3-693, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Mancini, M., Hoeben, R., and Troch, P. (1999). "Multifrequency radar observations of bare surface soil moisture content: A laboratory experiment," *Water Resources Research* 35, 1827-1838.

Nikodem. H. J. (1966). "Effects of soil layering on the use of VHF radio waves for remote terrain analysis." Proceedings of the 4th Symposium on Remote Sensing of Environment, 691-703, University of Michigan, Ann Arbor.

Perloff, William, and Baron, William. (1976). *Soil Mechanics, Principles and Applications*. Ronald Press Co., New York, NY.

Press, W. H., Flannery, B. P., Teukolsky, S. A., and Vetterring, W. T. (1986). "Numerical recipes, The art of scientific computing," Cambridge University Press, New York.

Robock, Alan, Schlosser, C., Vinnikov, K., Speranskay, N, and Entin, J. (1998). "Evaluation of AMIP soil moisture simulations," Global and Planetary Change, 19.

Roth, Kurt, Schulin, Rainer, Fluhler, Hannes, and Attinger, Werner. (1990). "Calibration of time domain reflectometry for water content measurement using a composite dielectric approach," *Water Resources Research* 26, 2267-2272.

Sullivan, P. M., and Bullock, C. D. (1997). "Soil moisture strength prediction model version H (SMSP II)," Technical Report GL-97-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Teng, W. L. (1993). "Relationship between satellite microwave radiometric data, antecedent precipitation index, and regional soil moisture," *International Journal of Remote Sensing* 14(13), 2483- 2500.

Terzaghi, K., and Peck, R. (1948). *Soil mechanics in engineering practice*, Wiley, New York.

Topp, G. C., Davis, J. L, and Annan, A. P. (1980). "Electromagnetic determination of soil water content: Measurements in coaxial transmission lines," *Water Resources Research* 16, 574-582.

Tuma, J., and Abdel-Hady, M. (1973). *Engineering soil mechanics.* Prentice-Hall, New York.

U.S. Army Engineer School. (1994). "Requirement for improved weather information," Memorandum for the Commander, U.S. Army Intelligence Center, Washington, DC.

U.S. Army Training and Doctrine Command. (1989a). FM 34-81-1, Appendix G, Washington, DC.

_____. (1989b). "Weather support for Army tactical operation," FM 34-81-1/Air Force Manual AFM 105-4, Washington, DC.

Vinnikov, K. Y., Robock, Alan, Qiu, Shuang, and Entin, Jared K. (1999). "Optimal design of surface networks for observation of soil moisture," *Journal of Geophysical Research-Atmosphere.*

Wraith, J. M., and Or, Daniel. (1999a). "Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: Experimental evidence and hypothesis development," *Water Resources Research* 35 (2), 361-369.

_____. (1999b). "Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: A physical model," *Water Resources Research* 35 (2), 371-383.

Wetzel, P. J., and Woodward, R. H. (1987). "Soil moisture estimation using GOES-VISSR infrared data: Case study with a simple statistical method," American Meteorological Society, Boston, MA.

Web sites:

Cold Regions Research Laboratory, U.S. Army Engineer Research Center http://www.crrel.usace.army.mil/bosnia/weather/weather.html.

National Oceanographic and Atmospheric Administration. (1998). "Flood Prediction Website, Soil Moisture Page", http://orbit-net.nesdis.noaa.gov:80/ora/ht/html/microwave-daily.html.

Soil Moisture Data Bank Site, http://www.climate.envscie.rutgers.edu, http://www.meto.umd.edu/~ala.

Appendix A
Tables

**Table A1
Soil Moisture Readings Converted from Gravimetric to Volumetric Units, May 1999**

| | | Test Location: Mud Lake: LA Fat clay soil | | Final Percent Difference from Gravimetric Measurements | |
| | | Adjusted Volumetric Water Content | | | |
Date	Weather	0-6 in.	6-12 in.	10 cm	20 cm
May-99					
5/11/99	Raining	24.70	19.63	4.89	11.05
5/12/99	Prtly Cldy	30.30	22.96	1.61	6.64
5/13/99	Prtly Cldy	25.43	21.80	9.94	3.85
5/14/99	Prtly Cldy	20.34	22.52	11.72	1.07
5/18/99	Prtly Cldy	31.24	23.98	9.54	4.08
5/20/99	Prtly Cldy	23.25	24.70	4.89	2.50
5/21/99	Clouds	23.25	24.70	6.80	0.62
5/24/99		31.24	26.88	4.77	6.82
5/25/99		29.06	26.88	0.90	7.36
5/26/99		26.88	26.16	0.72	6.32
5/27/99		24.70	26.88	3.59	6.51
5/28/99		22.52	26.16	6.28	4.72
	Average			5.47	5.13

Table A2
Soil Moisture Readings Converted from Gravimetric to Volumetric Units, June 1999

| | | Test Location: Mud Lake: LA Fat clay soil | | Final Percent Difference from Gravimetric Measurements | |
| | | Adjusted Volumetric Water Content | | | |
Date	Weather	0-6 in.	6-12 in.	10 cm	20 cm
Jun-99					
6/1/99		30.26	26.14	6.82	5.42
6/2/99		28.89	26.82	0.77	7.89
6/3/99		26.14	26.14	2.73	5.42
6/4/99		26.14	26.14	5.53	9.62
6/7/99		17.19	26.82	9.24	11.25
6/8/99		15.13	26.82	16.46	6.93
6/9/99		13.75	26.14	27.98	7.48
6/10/99		12.38	25.45	21.95	9.46
6/14/99		17.88	26.14	4.06	13.43
6/15/99		29.57	27.51	1.69	11.36
6/16/99		27.51	27.51	3.50	13.66
6/17/99		23.38	26.82	4.61	12.42
6/18/99		19.26	27.51	13.74	18.69
6/21/99		13.75	25.45	25.04	9.34
6/22/99		11.69	25.45	25.26	9.93
6/23/99		11.00	25.45	30.13	6.71
6/24/99		11.69	25.45	25.50	12.36
6/25/99		12.38	24.76	21.58	10.39
6/28/99		28.20	26.82	0.61	12.53

Table A3
Soil Moisture TDR Readings, May and June 1999

Date	Weather	Test Location: Mud Lake: LA Fat clay soil		Volumetric Water Content Moisture Proble Readings	
		Dry Density, by Weight Water Content			
		0-6 in.	6-12 in.	10 cm	20 cm
May-99					
5/11/99	Raining	27.25	24.5	34	27
5/12/99	Prtly Cldy	31.3	20.1	41.7	31.6
5/13/99	Prtly Cldy	31.05	23.55	35	30
5/14/99	Prtly Cldy	25.75	22.05	28	31
5/18/99	Prtly Cldy	25.8	22.1	43	33
5/20/99	Prtly Cldy	25.65	23.5	32	34
5/21/99	Clouds	26.65	24.4	32	34
5/24/99		28.4	23.45	43	37
5/25/99		29.6	23.2	40	37
5/26/99		26.5	23.05	37	36
5/27/99		26.55	23.6	34	37
5/28/99		25.55	23.8	31	36
Jun-99					
6/1/99		26.4	23.45	44	38
6/2/99		28.45	22.9	42	39
6/3/99		24.75	23.45	38	38
6/4/99		23.4	21.55	38	38
6/7/99		20.7	21.4	25	39
6/8/99		21.1	23.35	22	39
6/9/99		24.45	22.5	20	38
6/10/99		19.35	21.05	18	37
6/14/99		19.4	19.95	26	38
6/15/99		30.6	21.9	43	40
6/16/99		25.65	20.9	40	40
6/17/99		25.65	20.9	34	39
6/18/99		25.4	18.85	28	40
6/21/99		22.95	21.1	20	37
6/22/99		19.6	20.85	17	37
6/23/99		20.5	22.25	16	37
6/24/99		19.7	19.85	17	37
6/25/99		19.2	20.1	18	36
6/28/99		28.55	20.85	41	39

Appendix B
Derivation of Conversion Formulae

$$\theta_w = (S * w * G_s)/(S + w * G_s).$$

In this formula S is the degree of saturation:

where

$S =$ $(V_w)/(V_v)$ is volume of water in soil type/volume of voids in soil type

$\theta_w =$ $(V_w)/(V)$ is volume of water in sample/volume of sample, i.e., the volumetric water content

$w =$ $(W_w)/(W_s)$ is weight of water in sample/weight of the soil in the sample, i.e., the gravimetric (standard dry density) water content

$G_s =$ ρ_s/ρ_w is density of solids in the soil sample/the density of water in the soil sample, or unit weight of the soil sample/unit weight of water, i.e., the specific gravity of the soil type

Substitute in the formula all the above definitions along with the definitions:

$$\rho_s = W_s / V_s \qquad \text{and} \qquad \rho_w = W_w / V_w$$

and cancel like terms,

Then find:

$$\theta_w = ((V_w/V_v)*(W_w/W_s)*((W_s*V_w)/(V_s*W_w)))/((V_w/V_v)+(W_w/W_s*((W_s*V_w)/(V_s*W_w))))$$

$$= (((V_w/V_v)*(V_w/V_s))/((V_w/V_v)+(V_w/V_s)))*((V_v/V_w)/(V_v/V_w))$$

$$= (V_w/V_s)/(1+V_v/V_s) = V_w/(V_s+V_v) = V_w/V$$

Quid Erat Demonstrato (Q.E.D).[1]

---

[1] Mathematical terminology meaning, "That which was to be demonstrated." in Latin.

Appendix C
Index

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE September 2000	3. REPORT TYPE AND DATES COVERED Final report

4. TITLE AND SUBTITLE
Sensor Technology for Weather and Terrain

5. FUNDING NUMBERS

6. AUTHOR(S)
Andrew W. Harrell

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center
Geotechnical Laboratory
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/GL TR-00-9

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The purpose of this report is to review weather effects on soil moisture and combat engineering. It considers current means of obtaining soil moisture information from weather models, surface observation reports, and remote sensing sources. The methodologies used for different types of ground moisture probes, and, in particular, time domain reflectometers (TDR) are explained. It also explains how the measurements that the TDR probes give can be validated and calibrated for different soil types. Soil moisture information affects operational considerations for combat engineering and ground mobility considerations in particular. And, it has significant applicability to simulations and wargames.

The scope of this study was limited in several respects. It did not consider the details of operating the soil moisture probes or of implementing soil moisture measurements into simulations or wargames. Different ways of modeling precipitation or the areal flow of groundwater are not discussed. Tables of soil moisture values are currently provided for only one soil type and type of moisture probe. Thus conclusions about the usefulness of different types of probes for various soil types are limited in this respect.

14. SUBJECT TERMS

Combat engineering	Soil moisture probes	Validation of measurements	
Combat simulations	Terrain	Weather	
Soil moisture	Time domain reflectometers		

15. NUMBER OF PAGES
29

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT